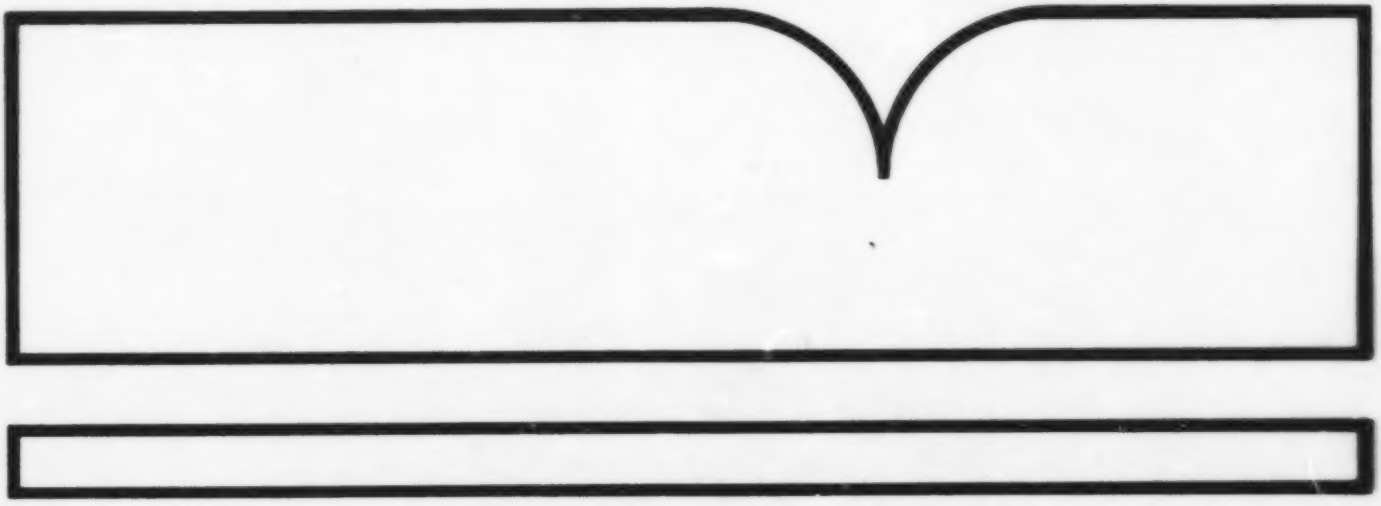
PB81-129959

Liquid Entrainment from a Mobile Bed Scrubber

(U.S.) Industrial Environmental Research Lab.
Research Triangle Park, NC

1977



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TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. REC
EPA-600/J-77-177	Journal Article	PB81-129959

4. TITLE AND SUBTITLE	5. REPORT DATE
Liquid Entrainment from a Mobile Bed Scrubber	6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
Seymour Calvert and Shui-Chow Yung (A. P. T.) and L. E. Sparks (EPA/IERL-RTP)	

9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Air Pollution Technology, Inc. 4901 Morena Boulevard San Diego, California 92117	11. CONTRACT/GRANT NO.

12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711	Journal article 14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES Coauthor Sparks' mail drop is 61; his phone is 919/541-2925. Published in Journal of the Air Pollution Control Association, Vol. 27, No. 8, 8/77, pp. 768-770.

16. ABSTRACT

The paper gives results of the measurement of liquid entrainment rate and drop size distribution in the exhaust gas stream from a mobile bed scrubber. The pilot plant scrubber was 46 cm square and was packed with 3.8 cm diameter hollow polyethylene spheres to a static depth of 25 cm. Entrainment flow depends on both gas and liquid rates. At a liquid/gas ratio of 6.7 l/cu m and a superficial gas velocity of 2.6 m/sec the entrainment flow rate was 0.0064 l/cu m; at 3.75 m/sec, it was 0.031 l/cu m. The mass median drop diameter was about 400 micrometers at a liquid/gas ratio of 6.7 l/cu m. The drop size distribution appears to be bimodal. Dye impregnated paper and cascade impactor techniques were used to measure drop size.

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17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Scrubbers	Stationary Sources	07A,13I
Liquids	Mobile Bed Scrubbers	07D
Entrainment		
Measurement		14B
Exhaust Gases		21B

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO. OF PAGES
Release to Public	Unclassified	
	20. SECURITY CLASS (This page) Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

EPA-600/J-77-177
Journal Article

Liquid Entrainment from a Mobile Bed Scrubber

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Liquid entrainment rate and drop size distribution were measured in the exhaust gas stream from a mobile bed scrubber. The pilot plant scrubber was 46 cm (18 in.) square and was packed with 3.8 cm (1.5 in.) diameter hollow polyethylene spheres to a static depth of 25 cm (10 in.). Entrainment flow rate depends on both gas and liquid rates. At a liquid/gas ratio of 6.7 l/m³ (50 gal/Mcf) and a superficial gas velocity of 2.6 m/sec (8.5 ft/sec) the entrainment flow rate was 0.0084 l/m³ (0.05 gal/Mcf) and at 3.75 m/sec (12.3 ft/sec) it was 0.031 l/m³ (0.23 gal/Mcf). The mass median drop diameter was about 400 μm at a liquid/gas ratio of 6.7 l/m³. The drop size distribution appears to be bimodal. Dye impregnated paper and cascade impactor techniques were used to measure drop size.

Scrubbing involves the energetic interaction of the gas stream and the scrubbing liquid, usually water. Often this means that entrained drops containing suspended and dissolved solids will exit from the scrubber system unless some means of entrainment separation is provided. Near 100% removal of entrained drops is essential for trouble-free operation of the scrubber system and high efficiency gas cleaning. Failure to remove drops can cause operating and maintenance problems for all components (e.g., fans, stack, reheaters, etc.) of the scrubber system down stream from the scrubber/entrainment separator. Failure to remove entrained drops containing suspended or dissolved solids can cause excessive particulate emissions.[1]

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Mobile bed scrubbers, which usually involve several stages of fluidized, wetted "ping-pong balls," have been used for scrubbing flue gas from coal-fired utility boilers. They can control particulate emissions and can also remove SO_x through absorption by a chemically reactive solution or suspension, as in lime/limestone scrubbing. Poor entrainment separator performance is cited as a problem in the use of mobile bed scrubbers on power plant flue gas.

Design of high efficiency entrainment separators requires knowledge of the entrained drop size distribution and concentration. Data on size distribution for drops smaller than 20 μm diameter are especially important, for without it the design of high efficiency entrainment separators is impossible. The experimental program reported in this paper was undertaken to provide data needed to improve the design of entrainment separators for mobile bed scrubbers.[2]

Experimental Program

Mobile Bed Scrubber

The mobile bed scrubber was a pilot-scale unit. It had a 45.7 cm (18 in.) square shell. The overall height of the scrubber was 3 m (10 ft), allowing 1 m for the fluidized bed plus 1.3 m of open column above the bed. Four flow straightening vanes were installed below the bed. Six Plexiglas windows (6 in. × 16 in.) were installed on two adjacent sides of the column so that the action of the packing and entrainment flow pattern could be observed during operation. The packing used for this was 3.8 cm (1.5 in.) diameter hollow polyethylene spheres and the depth of the packed bed was 25.4 cm (10 in.).

Air and water were used for study. Air flow rates to the scrubber were measured through calibrated pitot tubes. The pitot tubes were kept in one position after a complete traverse of the duct.

Experimental Procedures

The purpose of the experimental program was to measure drop size distribution and concentration of entrainment from

a mobile bed scrubber operating under fairly typical conditions. Air and water rates would cover common operating ranges, especially those likely to cause heavy entrainment.

In starting the experiments, the water pump and blower were turned on and the flow rates were adjusted to desired levels. After steady conditions were obtained, entrainment drop samples were taken at a location 76 cm (30 in.) above the top retaining grid.

After continuous operation of about 3 hr, the pump and blower were turned off. The change in liquid levels of the holding tank represented the sum of entrainment loss and evaporation loss. Evaporation losses were calculated from the scrubber inlet and outlet humidity data. Total entrainment loss was then determined by the difference. The concentration of entrainment was determined by dividing the entrainment loss by the total air volume passing through the scrubber.

Drop Sampling Methods

Chemically treated filter paper was used to determine the size distribution of large drops. Filter paper impregnated with 1% potassium ferricyanide and coated with ferrous ammonium sulfate was placed in the gas stream for a fraction of a second. Liquid drops collected on the filter paper make dark blue stains which can easily be counted and measured under the microscope. A correlation given by Chilton[3] was used to convert the blot diameter on the filter paper to the actual drop diameter. Due to the grain size of the chemical, it was used for drops with a diameter larger than 20 μm.

Big entrainment drops pose no collection problem because they are easy to catch. It is the fine entrainment drops which cause separational and operational problems. For proper design of entrainment separators information on fine drops, especially those which have diameters smaller than 20 μm, is required.

Drop size smaller than 20 μm diameter was determined by means of a cascade impactor. To prevent overloading the impactor by big drops, a pre-cutter was used ahead of the impactor. When pulling a sample through the sampling system at a gas flow rate of 14 l/min (0.5 cfm), the pre-cutter removes all drops bigger than 13 μm in diameter.

Early efforts to detect fine drops by cascade impaction were unsuccessful. It was found that fine drops evaporated even under nearly saturated gas environment. It was also discovered that due to reduced pressure in the sampling system, drops collected on impactor stage collection plates evaporated. To alleviate this problem, sodium chloride was added to the water to reduce the vapor pressure of water and serve as a tracer for analytical purposes.

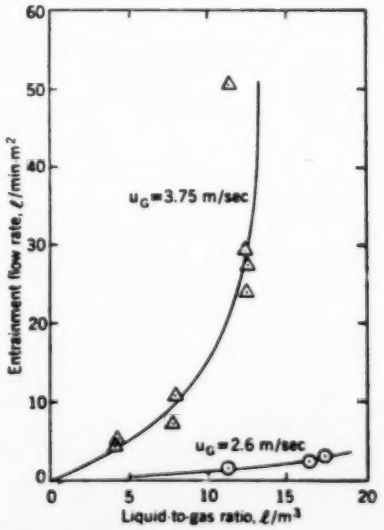

Figure 1. Entrainment flow rate.

The sodium chloride concentration in the drops caught by the pre-cutter was found to be the same as that in the scrubber liquid. This indicates that there was little or no evaporation of water from the drops as they leave the mobile bed and travel to the sampling point. Thus, the drop size distribution measured by the impactor was assumed to be the same as that generated in the mobile bed.

The drop size distribution was calculated from each impactor stage catch and the cut-diameter of the stage. Summation of the pre-cutter catch and the impactor catch gives the entrainment mass flow rate. The mass loading of the entrainment was then checked against that calculated from the water balance method discussed earlier. It was found that they were in fair agreement.

Because the entrainment flow pattern was observed to be highly irregular, drop samples were taken at several locations of the same cross-section for each operating condition. Isokinetic sampling was used for all cascade impactor runs.

Entrainment Results

Entrainment Flow Rate

Figure 1 is a plot of entrainment flow rate versus liquid to gas ratio (L/G) with superficial gas velocity as parameter. For a scrubber system, the entrainment flow rate generally increases as the gas velocity is increased. Increase of liquid flow rate also increases the rate of entrainment. Figure 1 clearly shows this trend. From Figure 1, for a constant superficial gas velocity, entrainment flow rate increased gradually with increasing L/G up to a value of L/G that corresponds to the flooding condition of the mobile bed. Further increase in L/G beyond this value will sharply increase the entrainment flow rate.

The liquid to gas ratio for a full size industrial mobile bed scrubber is about 6.7 l/m^3 (50 gal/Mcf) and the superficial gas velocity is about 2.7 m/s (9 ft/sec). From Figure 1, the entrainment flow rate is about 1 l/min-m^2 (0.025 gal/min-ft^2).

Drop Size Distribution

Large drop size distribution, as measured by the treated filter paper, follows the log-normal distribution. The size distribution so obtained is a number distribution. For practical usage, it is more convenient to express the size distribution based on mass instead of number. Since for a log-normal distribution, the number and mass distributions have the same geometric standard deviation, the following equation is used to convert number median to mass median diameter (see Orr[4]):

$$\ln \frac{d_{dM}}{d_{dN}} = 3 \ln^2 \sigma_g \qquad (1)$$

where d_{dM} = mass median drop diameter, μm
d_{dN} = number median drop diameter, μm
σ_g = geometric standard deviation

Figure 2 is a plot of mass median drop diameter versus liquid-to-gas ratio, with superficial gas velocity as a parameter. It can be seen that under normal industrial scrubber operating conditions, the liquid entrainment has a mass median drop diameter of approximately 400 μm. The geometric standard deviation for all test runs is approximately 1.7.

The fine drop size range had to be determined by the cascade impactor technique. Figure 3 is a sample plot of cumulative entrainment versus drop diameter for a superficial gas velocity of 3.7 m/sec and a liquid flow rate of 363 l/min (i.e., L/G = 58.5 gal/mcf).

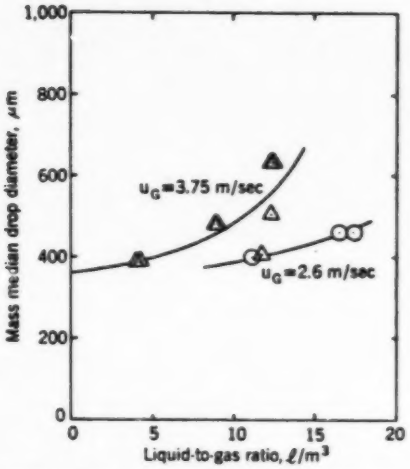

Figure 2. Mass median drop diameter of entrainment.

Pressure Drop

Pressure drop was measured across the mobile bed at several liquid to gas ratios. The pressure drops measured in this study are in fair agreement with the data of Douglas and Snider.[5]

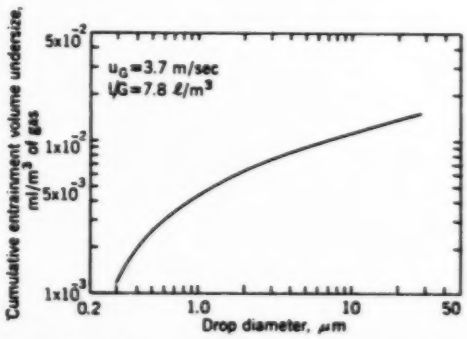

Figure 3. Cumulative entrainment volume versus drop diameter.

Discussion

Entrainment drop diameters varied from a few millimeters to submicron size. These drops might be generated by one or more of the following mechanisms: (1) Impingement of gas jets on a liquid film, (2) shattering of liquid drops due to impaction on the packing, (3) rupture of bubbles at the gas/liquid interface and subsequent drop formation. The third mechanism is considered the main cause of entrainment of liquid drops into the gas phase in a mobile bed. The bubble rupture model envisioned drops being ejected from the bed surface at high velocity into a concurrent gas stream rising uniformly at a rate equal to its superficial velocity through the bed. Thus, each drop thrust into the gas is then acted upon by inertial, gravitational, and drag forces. Some drops will be carried up continually and some only to certain heights, from which they fall back into the bed.

The liquid drops which are formed during the rupture of bubbles are of two distinct diameter ranges. Small drops less than 40 μm diameter are formed from the top of the bubble surface, and large drops about 1 mm diameter are formed due to the disturbances in the liquid phase following the bubble rupture. Formation of the small drops was observed by Stumpner,[6] who attributed drop formation to the rupture of the projecting dome of the bubble into fragments.

The data obtained in this entrainment study indicate that less than 1% of the mobile bed entrainment has diameter smaller than 10 μm. It is also found that the slopes of log-normal size distribution curves for fine drops and big drops do not match. One possible explanation is that the generation mechanism of large drops differs from that of fine drops and the size distribution for all drops is therefore not log-normal but bimodal.

Sampling point location has great influence on the sampling of large drops. In this study, entrainment samples were taken 76 cm above the top retaining grid of the mobile bed scrubber. If the samples are taken at a higher elevation, large drops will settle out. This will change both the entrainment loading and the drop size distribution. For example, for a gas superficial velocity of 2.6 m/sec, all drops larger than 600 μm in diameter would settle out of the air stream if the height was sufficient. This is because the terminal settling velocity of a 600 μm diameter water drop is about 2.6 m/sec.

The information obtained in this study is useful in specifying the performance requirement of an entrainment separator. If the total dry particulate emission from the mobile bed is to be 0.025 g/m³ (0.01 gr/scf) and if one wants to limit the particle loading due to entrainment to 5% of total emission, the residual particle concentration after evaporation of entrainment would be 1.25×10^{-3} g/m³ (0.0005 gr/scf). If the entrainment contains ten % solids by weight, the wet entrainment loading could be 1.25×10^{-2} ml/m³. As Figure 3 shows, it would require the separation of all entrainment larger than 10 μm diameter to meet this limit.

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